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Managing CAD Systems in Mechanical Design Engineering

David C. Robertson
Thomas J. Allen

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Massachusetts Institute of Technology
Sloan School of Management
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The International Center for Research on the Management of Technology

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Sloan School of Management
Massachusetts Institute of Technology
50 Memorial Drive, E52-171
Cambridge, MA 02139-4307

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Abstract

Despite the importance of and our long history with Computer-Aided Design (CAD) systems, our understanding of the systems is limited. To understand the role CAD systems are playing in the design engineering processes of different companies, field interviews were conducted at ten companies. Design engineers, managers, CAD support personnel, and others were interviewed to understand the management of CAD systems in mechanical design engineering.

The result of the field research is the conclusion that managers view CAD technology in one of three ways: as physical capital, as supporting or extending human capital, or as enabling improvements in social capital. Further, the value received from the technology will depend directly on how managers view the technology. Managers who see the systems as physical capital (i.e. electronic drafting boards) will receive some benefit; managers who view the systems as enabling improvements in social capital will receive the greatest benefit from the technology.

The characteristics of each of the three views of CAD technology will be discussed, as well as the barriers that prevent companies from realizing the full benefit of CAD technology.

1. Introduction

In recent years, industry has focused a considerable effort on reducing product development times. Many believe that the appropriate use of Computer-Aided Design (CAD) systems may aid significantly in achieving this goal. Many companies have made large expenditures on CAD systems- expenditures have reached $100 million for a single company's hardware and software. The market for Computer-Aided Design, Engineering and Manufacturing systems will reach $7.7 billion in 1991 and is projected to reach $25 billion by the middle of the decade[1].

There has been some debate, however, over the benefits of CAD systems [17]. While many organizations have made large investments in CAD technology, some of these organizations do not believe their money was well spent. Managers in these organizations are not seeing the benefits they expected from their systems [17].

In the following sections, the results of an investigation into the management and use of CAD systems in ten manufacturing companies are reported. The goal of the research is to understand how engineers and managers perceive CAD systems, how work is restructured when CAD is used, and what barriers prevent the effective use of CAD systems. In the next section, an introduction to CAD systems is presented, followed by a brief review of the current literature relating to Computer-Aided Design.

2. CAD Systems

CAD systems are defined in this paper to be those computer tools that support the design and design engineering processes. This definition thus includes computer tools normally classified under Computer-Aided Design, Computer-Aided Drafting, and Computer-Aided Engineering (CAE). The greatest use of these tools is in the support of mechanical design and engineering [30]; it is that area of application that will be addressed in the present paper. More information about the features and functions of such software can be found in [5],[30].

CAD systems can potentially lead to many important benefits for organizations. For example, CAD systems can potentially reduce the length of the product development cycle and improve relationships with both vendors and customers. The literature provides many descriptions of CAD applications that have helped to reduce product development time ([4],[7],[8],[18],[36],[40],[45]). A shorter design cycle allows companies to respond more quickly to competitive challenges, incorporate newer technology into products, and charge higher prices for unique features.

CAD systems can also help improve a company's links with its vendors and its customers [9],[15]. For example, one airframe manufacturer provides major customers with a CAD terminal. If a problem occurs in the field, maintenance

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[1] Source: Daratech, Inc., Cambridge, MA.

personnel can access the CAD design file and either (1) communicate by phone with the manufacturer's support personnel (who can access an identical CAD file) or (2) make comments on a CAD file and send the file electronically to the manufacturer. In either case, communication between the manufacturer and its customers is faster, there is less ambiguity in the information communicated, and there is less travel required of the manufacturer's support personnel to customer sites.

Thus CAD systems have been shown to have some major benefits in some organizations. In the next section, a review of the literature on the implementation and use of CAD systems in organizations is presented.

Research on CAD Systems

There are five categories of research results that will be reviewed: industry case studies, benchmarking studies, implementation factors research, individual work change research, and organizational change research.

Industry Case Studies

Industry case studies present specific examples of CAD technology in specific organizational contexts. The literature in this area describes applications of CAD technology that reduce product development time [4],[8],[16],[20],[28],[38],[39],[40],[45] or improve product quality [14],[18],[41],[42]. For example, Swerling [37] reports that the use of computer tools cut the development costs for the IBM 3081 computer by 65%. Bull [7] reported that CAD/CAM improved productivity for product development by 150%. Chrysler estimates that computer tools will cut the development cycle for new cars from five years to four or less [18]. Kodak [16] linked product designers and tool designers through a common CAD system and were able to develop the "Fling 35" camera from project start to shipping approval in 38 weeks. They estimated that this CAD system helped them reduce development costs by 25%.

Unfortunately, with few exceptions, this category of research provides managers little insight into how to achieve similar gains in their own organizations. These studies focus on the specific characteristics of the new technology, and ignore the other technological and organizational changes that must be made to utilize the technology to full advantage. With few exceptions (e.g. [36],[43]), it is not clear how the results achieved in these studies could be repeated in other organizations.

It is important to note that the large gains reported in the trade literature are hardly guaranteed- some managers believe that the introduction of CAD systems has hurt productivity (cf. [17]). If the introduction of CAD into an organization leads to no change or a decline in productivity, it is unlikely that this negative finding would ever be reported in the trade literature. Thus we cannot count on the literature to accurately reflect the average company's experiences with CAD systems.

Benchmarking Studies

The second category of research, benchmarking studies, test the performance of CAD systems against drafting boards. Such studies show productivity gains from 25% to 350%, depending on the nature of the task [26]. Other studies show productivity increases from 5:1 to 20:1 [35]. It is often difficult, however, to achieve these results in organizations [35].

Implementation Research

In the third category of research, implementation research, many factors which can affect the success of a CAD implementation effort have been identified. The factors most frequently cited are the role of management, the physical layout of the CAD system, and the shallow learning curve of CAD systems. Such implementation factors are important to the successful use of CAD systems (cf. [33]).

Many studies have found that the role of the supervisor is critical to the success of a new CAD system. Brooks and Wells [6] and Strachan et al. [36] both point out that it is the supervisor who structures work for the CAD user, and thus the supervisor must change the way in which that work is structured and assigned for CAD systems to be used effectively. Manske and Wolf [29] found that managers' conceptualization of CAD was the key determinant of the ultimate use of the systems: if CAD systems were seen as drafting tools, then the systems led to a downgrading of skills in the subordinates' jobs. If the systems were seen as useful for improving front-end thinking about designs, then use of the systems was found to lead to an upgrading of skills. Forslin et al. [19] found that it is the manager that must consider the organizational changes necessary to achieve integration with CAD, and that few managers considered such changes. Finally, Lee [23] found that worker-management trust was a key determinant of CAD implementation success.

Both Brooks and Wells [6] and Strachan et al. [36] discuss the importance of the physical layout of CAD systems on implementation success. Brooks and Wells argue that, while locating CAD terminals centrally eases the training of users and the organizational control over use, central locations tend to increase the psychological separation between the users and their management.

Strachan et al. [36] and Salzman [35] both discuss the learning curve effects of CAD. Both argue that it is difficult for the user to gain proficiency in the technology. Salzman points out that many systems arrive at the user site with software bugs, and that the difficulty of learning the technology is compounded by these bugs-- it can be difficult for the user to distinguish between a user error and a system error. Majchrzak and Salzman [27] point out that use of the systems is hindered by the complex set of commands and syntax for executing those commands that is inherent in many CAD systems.

Other implementation factors that have been identified are union rules, workstation access, resistance to change, and inadequate functionality [36].

Individual Work Change Research

In the fourth area of research, changes in individual work associated with the use of CAD systems, some research has focused on how use of CAD systems is related to the range of skills required by users' jobs. One early study argued that CAD systems would lower the skills required in users' jobs [13]. Norton [32] found that CAD increases the skills required in users' jobs for senior employees, but reduces the skills required for lower-ranking users. Wingert et al. [44] argue that lower-ranking employees will be the only ones affected by CAD systems, and that CAD will *increase* the range of skills needed. Manske and Wolf [29] found that skilled jobs retain their skill level, while some lower-skilled jobs disappear. Other mixed findings can be found in [18]. More recent work suggests that CAD systems lead to an increase in the skills required by users [1],[35].

Liker and Fleischer [24] found that the introduction of CAD systems changed the job content of CAD users and non-users alike. They found that non-users were older, and tended to be assigned maintenance and supervisory tasks, while users worked on newer designs. Interestingly, they found no difference in attitudes toward CAD or in overall job satisfaction.

Organizational Change Research

The final area of research is the organizational changes associated with use of CAD systems. The findings in this area have been inconclusive. Collins and King's [12] empirical work found that, while individual job content is affected by use of CAD, work group structure is unrelated to CAD use and is better determined by overall work technology. Forslin et al. [19] found that CAD systems had little effect on the overall functioning of the organization unless such effects were an explicit objective of the introduction of CAD technology. Adler [2] found that, while there were gains at the individual level with the introduction of CAD, such gains were not translated to the organizational level. For example, while CAD helped users produce drawings faster, the overall flow of drawings through the organization was unchanged. Majchrzak and Salzman [27] sum up the findings in the current literature well: "few organizations [were] willing to make the necessary procedural, structural, and cultural changes to achieve design and manufacturing integration, despite this being the ostensible reason for purchasing the CAD system" [27: pg. 177].

One overall finding from the above literature is that CAD systems do not necessarily *cause* any changes to occur to the jobs, work processes, or structure of an organization- they only enable changes. The eventual use of a CAD system is as much a result of managerial decisions, individual predispositions, and organizational environments as it is of the features of the system. Thus different organizations can (and do) use the systems quite differently. CAD systems are a complex technology, and their application in organizations tends to reflect the characteristics of the organization as much as the features of the technology [2],[3],[27].

Another clear finding in the literature is the importance of the manager's role in the implementation and use of CAD systems. Managers have a strong voice in the deployment of CAD and in the assignment and structuring of work tasks. As the above literature shows, different managers can perceive and manage CAD differently, and thus experience different results with the systems.

The research reported below focuses on the role of the manager. Interviews with managers, subordinates, CAD support personnel, and others are analyzed to understand the issues facing the managers of engineers using CAD. In the next section, a framework is presented which will be used to organize the data from the field interviews. Following that, the interview data is presented.

3. The Research Framework

The concepts of physical, human, and social capital that are defined and developed in this section will be used to analyze the observational data from the field. Physical, human, and social capital can be seen as resources in the product development process. A good manager will develop and use each to its maximum advantage. Physical Capital comprises the machines and equipment that are used to add value to a product, or allow a product to be developed more efficiently (i.e. more quickly or less expensively). The cost and value of this type of capital are relatively well understood by managers. Human Capital comprises the skills and knowledge of a company's workers that allow them to add value to a product during its development, or to develop a product more efficiently. Managers are usually willing to pay the cost of developing this capital, even if they cannot quantify the value to be received. For example, managers and companies will release employees for weeks, months, or even years so that they can attend seminars, classes, or degree programs. This is done with the assumption that the employee is worth more to the company upon return.

The third type of resource is Social Capital [11]. Social capital resides in the relationships between individuals that allow them to add value to a product during its development or develop a product more efficiently. Social capital is not a property of the individuals in an organization- it is a property of the relations among individuals. As with physical and human capital, social capital is not completely fungible– the development of a certain type of social capital may be productive for certain tasks, but have no effect or be harmful for others. Managers often do understand that the ability of their employees to work together to accomplish goals has a great deal of value, and that developing social capital can return large benefits. Many organizational actions such as forming ad hoc teams, creating liaison roles, or adopting a matrix structure are undertaken to improve social capital.

4. Research Method

To understand how CAD systems are managed, field interviews were conducted at

ten manufacturing companies. The ten companies produced a wide range of complex mechanical products, including jet engines, airframes, power generation plants, copiers, and automobiles. The topics covered in the interviews included:

- The nature of the design engineering process,
- The features and capabilities of CAD systems,
- The changes in the process and structure of the organization that have occurred since the introduction of CAD technology, and
- The nature of the companies' management and their attitudes toward CAD systems.

Interviews were conducted with a broad cross section of roles, including design engineers, managers, CAD support personnel, and others. A total of 46 design engineers, 29 managers, and 20 CAD support personnel were interviewed in the ten companies. In addition, 35 individuals from other groups which assisted the design engineers in their work (such as analysis or producibility groups) were also interviewed. An average of two days was spent in each company.

The goal of the interviews was to understand the design engineering process, the role CAD systems play in the process, and managers' perceptions of and reactions to CAD systems. Investigating the use of all computer tools throughout the product development process was outside the scope of the research; it was decided to focus solely on the use of CAD systems in the design engineering phase of the process.

5. The Design Engineering Process

Many authors have characterized the product development process as passing through a number of stages. Myers and Marquis [31], for example, describe five stages: recognition, idea formulation, problem solving, solution, and utilization and diffusion. Roberts and Frohman [34] call for six by designating Myers and Marquis' "solution" "prototype solution" and adding "commercial development" as an additional, and we might add, a very important phase. Clark and Fujimoto [10] return to five phases, based on the automobile development process: concept generation, product planning, design engineering, process engineering, and production.

Building on these earlier formulations, we will present another characterization of the product development tailored to the current research. The goal is to build a general model of product development which corresponds well to the many different complex product development processes studied.

In the products studied, the product development process can be described by six phases. In the Recognition phase, the company identifies a need for a new product or a potential application of a new technology. In the Idea Formulation phase, a design specification for a new product is developed. In the Design Engineering phase, this specification is translated into a set of detailed drawings so that a prototype product can be built. In the Prototype Refinement phase, defects are

removed and additional improvements may be made to the prototype. After the final version of the design is decided upon, the Process Engineering phase begins. In this phase, the detailed design specifications are used to create a process design, which may include flow charts, plant layouts, tool and die designs, etc. When this phase has been completed (as judged by the success of a pilot production run), the Utilization and Diffusion phase begins.

This research focuses on the Design Engineering phase of the product development process. In the next section, a typical design engineer's job is described. Following that, the observations from these interviews are presented.

The Design Engineer's Job

Engineers in the design engineering phase of product development are often organized functionally around either parts of the product or types of analysis. Design engineers may be assigned a part or group of parts and are then responsible for completing the design of those parts (and are often responsible for the parts during the later phases of product development). The organization of a typical work process (for the companies studied) can best be described by an example.

The design engineers responsible for the engineering of a gas turbine engine are usually organized around the different parts of the engine- the compressors (which compress and heat air), the turbines (which drive the compressors), the burners (which mix compressed air with fuel and ignite the mixture), the shaft and bearings (on which all rotating parts turn), the static structures, and the overall systems (for circulating air, fuel and oil around the engine). The engineer responsible for the engineering of a turbine blade would report to the manager of a Turbine group, which is responsible for all parts in that area of the engine. This engineer would work with the engineers responsible for the parts adjacent to his: engineers in the Static Structures group, the Shaft and Bearings group, the Systems group, and the group responsible for the next and previous stages in the engine (possibly a Compressor group and a Burner group).

In addition, this engineer may be required to work with many other groups. For the design of a turbine blade, the design engineer must work with someone from the Aerodynamics group, who provide airfoil shapes to the engineer; the Aeromechanics group, who test for vibration properties; the Heat Transfer group, who test the temperature gradients to ensure that the blade is cooled properly; the Stress and Life Analysis groups, who check the stresses on and wear of the blades and predict how often they would need to be replaced in the field; the Drafting group, who add dimensional information and additional views to the design to prepare the design information for manufacturing; one or more testing groups, who are responsible for completing the necessary engine certification tests; a performance group, which tests the output of the engine to ensure that specifications are met; and a Manufacturing representative, who ensures that the part can be built for a reasonable cost in a reasonable period of time. Other groups, such as a materials

research laboratory, may occasionally be involved.

The engineer responsible for a part must balance the demands of each group, as well as work within his own constraints. The Aerodynamics group prefers thin airfoils for optimal airflow characteristics, while the Aeromechanics group prefers thicker, stiffer blades to reduce vibration. The Heat Transfer group may require cooling channels within the blade, which may conflict with both the Aerodynamics and Aeromechanics groups' goals. Against each of these groups' demands must be balanced the cost and weight of each design alternative. Finally, a design which works well may not be durable, maintainable, or producible, and thus may have to be redesigned, necessitating changes undesirable to any or all groups.

The overall job of the design engineer is one of balancing conflicting requirements. Unfortunately, this is often done by incorporating different perspectives sequentially and iteratively converging on a solution (cf. [8]). Many of the design engineers, when asked to describe their job, used the term "project manager." They describe their job as one of coordinating a group of people who carry out the bulk of the design and analysis work. Most of the design engineers' time is spent coordinating efforts between the different groups.

Design engineers also perform design and analysis work on their own. The analysis performed by the engineers was largely described as "quick and dirty" analyses to understand the feasibility of new ideas or to check the accuracy of results generated by other analysis groups. The engineers do perform some design work, which involves generating new design possibilities. This (in most companies) is the smallest part of design engineers' work.

6. The Field Interviews

Below are presented the summarized results of the field interviews. Quotes, with names and products disguised where necessary, are provided where appropriate. The findings have been organized into three categories, corresponding to different managerial views of CAD systems.

CAD Systems as Electronic Drafting Boards

Some managers saw CAD systems as electronic drafting boards. This is understandable, as many managers gained their engineering experience before CAD systems were developed and may not have had the time to learn the new technology. Managers of this type often view CAD as a drafting board with some additional (and, to them, mysterious) features. They see their subordinates' performance improving on some tasks, but declining on others. One engineer, describing his manager, stated:

> Ed [the manager] will come out and ask us about a design he wants done. He'll show us the design and say "does the magic button work for this one?" Meaning is it faster to do this on CAD? Sometimes it is,

> sometimes it isn't.... With new [designs], getting the geometry into the system can take longer than with a drafting board. If we have a similar [design] in CAD, we can change it to get the job done quickly.... Ed knows that CAD's better sometimes, but he doesn't really understand why.

"Ed" (the engineering manager) stated:

> I put all the work I can on CAD. Sometimes CAD's slower and we have to go with the drafting board.... We've also had trouble freeing up our guys for CAD training- it takes two weeks and we can't afford to lose a guy for that long. Since the layoff we've been undermanned and overworked.

Many managers expressed frustration at the task of managing workers on CAD, a technology they did not understand. For some tasks, the productivity advantages of the CAD systems were undeniable- the production of a slightly different version of a previously designed product was accomplished by the CAD system very quickly. Yet some managers complained that it was more difficult to manage work done on CAD. One manager stated:

> I used to be able to walk by the drafting board and tell whether progress had been made. Now I have to go in and figure out how the CAD model changed. That's a lot harder.

CAD Systems as an Engineering Support Tool

Other managers believed that designing on a CAD system is a process very different than designing on a drafting board, especially if the CAD design is done in three dimensions. Such managers would require that design work be done in three dimensions; they stated that, while designing in three dimensions is a more difficult and more time-consuming process, it provides significant benefits. One manager stated:

> Parts are more complex to design the first time with 3-D [CAD]. You have to think the whole part through. Even with color and levels, it's still really complex.... I think CAD leads to simpler designs just because of the lazy factor. It's harder doing design in 3-D so you tend to go for the simplest solution.

An engineer stated:

> The way castings used to work, we'd design cross-sections, then send these out to the casting vendor. They'd have to interpolate between the cross-sections and sometimes it'd take one or two iterations before they'd get it right. Now we define the whole surface.... It's harder to

> design the surface. Getting it right takes about 50% longer.... You really have to plan ahead how you're going to do the surfaces[2].

Some managers also stated that the analysis features of the systems allowed for a better simulation and testing of the design before any hardware was built. An automotive engineer stated:

> One of our tests for a new vehicle is to run it through pot-holes on the test track.... Before, when we'd find [a physical failure with a part], we'd try to figure out the problem from the part-- a hit or miss operation. Some of the changes we'd make would annihilate tooling[3]. Now we create a model and run it over the pot-hole in CAD. We get the CAD data, we know loads from the specs up front, and we know the other boundary conditions for the Finite Element model. Now we iterate more and find the problem better.
>
> We did reality checks and found the model was accurate- our results at 17 miles per hour were the same as the results at [the test track] at 15 miles per hour.... At the track, you've got a guy in a car going through pot-holes bouncing around inside. How well is he going to keep the car going at exactly 15 miles per hour anyhow?
>
> Doing this analysis lengthens the process by two to five weeks upstream, but the downstream savings is three iterations in tooling and testing out of six. The three iterations take six to twelve months.... I did four iterations on the suspension this morning, which would've taken eight months in the field.

A similar experience was reported in a gas turbine engine manufacturer. To certify an engine for commercial use, the engine must survive the ingestion of birds (as this can occur during flight). The intersection of a simulated bird with a simulated turbine blade was used to test the performance of the engine in this respect. Again, the results of this simulation improved the engineers' understanding of the design and the quality of the first prototype.

CAD Systems and Communication

CAD systems in many companies were used to improve communication. Some engineers, when trying to explain a design concept to others or resolve a design conflict with others, will often coordinate with others in front of a CAD terminal. One manager stated:

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[2] This company did not send the CAD surface geometry to its casting vendor. The vendors at the time of the interview were not able to accept CAD data.

[3] I.e., require major changes in the tooling of the production process.

> With CAD, you can create different views for different tasks. This cuts the drawing time- you don't have to recreate the design each time. Also, CAD is better than drawings. It takes a lot of practice to understand someone else's drawing. Drawings get pretty complex, there's a lot of lines, and you can get optical reversals and other problems.... You can also shade the CAD model if you do surfaces, which makes it look a lot more realistic.

Another use of CAD systems as a communication aid was found in a large airframe manufacturer. This company created a "CAD Design Review Room," in which a CAD terminal display was projected onto a large projection-TV screen. When engineering changes to a part were requested or required, all parties involved would meet and review the change, with the engineer in charge of that part using the CAD terminal. The CAD drawing of the part in question was changed, rotated, added to, or simplified by the engineer on the terminal. One manufacturing engineer discussed the changes that the use of the room had on his job:

> With the [CAD design review room], the conflict with the [design engineers] is a lot less- we get things resolved earlier.... The difference is we feel like our comments are invited. Before, we felt like we were on the outside, like we had to force our opinions on the design guys.

A manager in the same company stated:

> One thing the [design review] room changed was the number of reviews we have. Before, we'd only meet for fairly major [design] changes. Now, we'll meet for the least little design change. We have a lot more meetings than we used to.

Engineers will also use the systems to coordinate with others by accessing others' design work directly. Many design errors are simple gaps or interferences between parts. Engineers in some companies could access other parts on their CAD systems and check the fit of those parts with their own.

Another example of coordination through CAD systems is the use of standard parts libraries. The Purchasing organization chooses a set of fasteners and purchases them in bulk. The geometry and characteristics of these parts are placed in a CAD library which engineers can access. Thus engineers can easily tell which fasteners are preferable without having to read any releases or call anyone in Purchasing. The coordination between these departments is more efficient.

A change that occurred in one surveyed organization was the removal of the group responsible for integrating the different parts of a large project. This group was replaced, in effect, by a CAD file containing the designs for the different parts of the product. The central CAD file was accessible by all and was used by all engineers to

ensure that the parts they designed fit with the rest of the project. Each engineer can be responsible for understanding the fit of that engineer's part with the other parts around it, and for resolving any problems that occur.

A similar example was found in an automobile manufacturer. The conceptual design of a new automobile is done through the creation of a clay model. When the conceptual design of the exterior of the new model is complete, the clay model is digitized and this information is sent to the Packaging group (as well as other groups). The Packaging group determines the placement of all components within the automobile. "Envelopes" for each area of the car are created, which define the outlines of the space for the passenger compartment, luggage compartment, engine, transmission, drive train, suspension, gas tank, electrical components, etc.

This Packaging group recently started building full three-dimensional CAD models of all components, and now transfers a CAD file to all groups, defining the envelopes exactly for the groups. With this CAD model, each group now knows exactly where it must place its parts and with which group it must negotiate if more space is needed. The productivity "impact" on the Packaging group is large and negative- it takes much longer to build the full three-dimensional model of all major auto components. The result, however, is a more complete specification of the component envelopes for downstream processes. Managers downstream report that this better definition of the space allocation under the hood leads to less conflict between groups, as fewer misunderstandings occur. This in turn has led to better relationships between groups and greater productivity. Furthermore, this automobile manufacturer believes that the overall development time will be cut significantly.

7. Discussion

Managers in every company surveyed exerted a large influence over the design engineers and their use of CAD systems. Managers' attitudes and knowledge of the capabilities and limitations of CAD systems were a crucial determinant of how effectively the systems were used (cf. [3],[6],[19],[21],[29],[36],[43]). In this section the concepts of physical, human, and social capital will be used to categorize managers' attitudes toward CAD systems.

Managers views of CAD systems can be classified into three categories corresponding to the three types of capital discussed earlier. Some managers saw CAD systems as physical capital, some as supporting and extending human capital, and some as enabling improvements in social capital.

Physical Capital

Some managers saw CAD systems as physical capital, as electronic drafting boards. Managers in this category (such as the manager who saw the CAD system as a drafting board with a "magic button") did realize some productivity gains from the system. The engineers in these departments, however, would openly express

frustration that much more could be done with the systems.

Human Capital

Some managers understood that CAD systems could provide the design engineer a better understanding of the design; they saw CAD systems as supporting or extending human capital. Managers in this category believed that CAD systems allow the design engineer to understand the geometry and characteristics of the design more fully. The detailed representation of the design, coupled with sophisticated rendering capabilities, allow the design engineer to represent the design more exactly and in more detail. Design engineers working at a CAD terminal report a "resonance" with the design- an ability to understand the design in great detail- that is not as easy to achieve with a drafting board. With CAD systems the design engineer has in front of her a tool that allows her to work with the design as it will appear when it is produced.

Managers in this category allowed their engineers the time necessary to complete a full three-dimensional model CAD model, as they realized it would improve the engineers' ability to understand the design (and to communicate it to others). These managers would also allow the time necessary to perform detailed analyses of the designs, as they gave the design engineers a better understanding of the characteristics and limitations of different design alternatives.

Social Capital

The third category of managers saw CAD systems as enabling improvements in social capital. The managers in the previous group, while understanding the capabilities of CAD systems as individual support tools, did not understand the ability of CAD systems to improve communication between individuals in different groups. These managers took advantage of the ability of CAD systems to act as a *common language* between different specialties and (where possible) used CAD design review rooms. They understood that a central CAD file unambiguously communicated design information around a company, enabling improvements such as the removal of the integrating group in one company and the improved layout from the automobile Packaging group.

Of the 29 managers interviewed, 16 viewed CAD systems as physical capital, 6 viewed CAD systems as supporting or extending human capital, and 7 viewed CAD systems as enabling improvements in social capital. This rating is the subjective judgement of the authors, and is based upon the interviews with the managers and their subordinates, as well as the actual use of CAD systems by the managers' subordinates. Managers were not asked to classify themselves.

In every company, there was evidence of different applications of CAD systems. There was always at least one engineer building three-dimensional models, checking the fit of the model with other engineers, analyzing the model with whatever tools were available, and explaining the design to others with the CAD

model as an aid. Engineers such as this had to fight management in some companies, but were supported by management in others.

8. Factors Affecting the Use of CAD Systems

There are many organizational policies and actions that affect how CAD systems are used and to which uses the systems can be applied. These policies and actions make possible the use of CAD systems for various activities, and are thus referred to as enablers. These enablers fall into three general categories: *basic enablers*, which allow the use of CAD systems as physical capital; *human support enablers*, which allow the systems to support and extend human capital; and *coordination enablers*, which allow improvements in social capital.

These "enablers" appear to form an inclusive scale. Basic enablers, which are necessary to effectively use CAD systems as electronic drafting boards, are necessary for the use of the systems to support human capital and to enable improvements in social capital. Similarly, the human support enablers are also coordination enablers.

These factors should not be confused with the implementation factors reviewed earlier. These should be seen as factors that can enable continued CAD-based improvements in the performance of the engineering process. These improvements can occur during CAD implementation or after.

Basic Enablers

Good Training: Many training classes (including those offered by most vendors) do very little to teach an engineer how to apply CAD technology to the tasks at hand. More often, these classes provide an introduction to features, but little guidance on how those features should be used. By the time the user has learned how to apply the basic features to his or her own job, the more advanced features have been forgotten. The best CAD training classes require that the engineer bring a design problem from the workplace to class, and complete that task by the end of the class.

Good Support: A good support group will provide assistance to users in learning new features, will keep the system operational, and will respond to users' requests to tailor the system to company-specific tasks. A good support group must be accessible and must respond quickly to requests.

Fast Hardware and Efficient Software: Many engineers are working on outdated hardware and software. Engineering is a process which requires great mental involvement with the work. Having concentration broken by slow response time can drastically affect productivity. With the cost of machine power falling rapidly and the cost of labor increasing, it is understandable why many companies wait to upgrade their systems. Yet without this, design in three dimensions can be too difficult. Unfortunately, response time is not dependent on machine hardware alone- poor response time can be caused by poorly designed software as well.

Ease of Use and Usefulness: A system that is overly complex in its execution or one that lacks functionality will not allow organizations to gain the full advantage of CAD technology. The complex command syntax and unnatural way that design primitives must be manipulated can make CAD-based design difficult [27].

Human Support Enablers

Managerial Understanding of CAD Systems: If managers do not understand the capabilities and limitations of their subordinates' systems, they cannot adequately judge their subordinates' behavior. The drafting board provided the manager with instant feedback on subordinates' progress; measuring work progress with CAD systems requires that the manager understand when progress has been made on a CAD model. This is much easier if CAD capabilities are known. Further, managers who understand CAD technology can more accurately gauge the benefits of a proposed new application, and can better guess whether the financial and learning curve costs are justified.

Allowing Three-Dimensional Usage: Engineers sometimes resist designing in three dimensions. The design takes longer to complete and must be thought through more completely; much greater concentration is required in the process. Yet designing in three-dimensions allows other activities to occur:

- Designing in three dimensions with surfaces or solids provides a producibility check. A rule of thumb is: "if it is difficult to design with surfaced or solid models, it is impossible to manufacture." In addition, it is much easier for an experienced manufacturing engineer to check a three dimensional model for producibility.
- When designing in three-dimensions there is less duplication of effort- all engineers can work from the same model. When designing in two dimensions, the analysis groups must construct their own three-dimensional models, which may be different from one another. The different groups may also want to see the model from a different angles, or see different information about the model. Only with three-dimensional representation can all groups work from the same model.
- With three-dimensional design, there is a greater ability to explain the design to others, as the design can be rotated and (if surfaces or solids are used) the design can be shaded and hidden lines removed.

Simplified Links to Analysis Packages: Getting CAD data to analysis packages can be difficult. Some engineers reported that the design geometry had to be re-entered by hand into the analysis package. Enabling the direct transfer of CAD geometry to analysis packages enables more and better analyses to be performed.

Coordination Enablers

Required Use of CAD: One major step that many companies never make is the requirement for CAD use, i.e. the requirement that all parts for new products be created on CAD systems. Often, the learning curve for CAD systems, coupled with

strict deadline pressures, will inhibit the use of CAD systems. Those engineers who do not use CAD will impose a cost on those who do and who need to access design information from the non-CAD user.

Moving the Official Design Document Onto CAD: When CAD models are used to generate a paper document which becomes the official design document, the urge to make last-minute changes to the paper document only can be quite strong (it may take ten minutes to erase and change the paper, while accessing the file on CAD, changing the model and generating a new drawing can take hours). Yet coordination through the CAD data files is much more difficult if all design information cannot be accessed, or the design information on the system is not current.

Maintaining One Model: Different groups may need to see the design in different ways. Returning to the turbine blade example, an Aerodynamics group is concerned with airflow lines, while an Aeromechanics group is concerned with cross-sectional surfaces. A strategy which requires that each group construct its own model is much less efficient and more prone to errors than if a single model is translated for all to use, or if the initial model is complete enough for all to access.

Adding Intelligence to the Design: If there exists an organizational norm that the greatest amount of information possible about the design should be placed in the file with the geometry, then the CAD file will provide a richer source of information to those who must access it, and thus make coordination through CAD more effective.

Use of CAD File Naming Conventions: A naming convention for design data files can aid in the location of the design data by engineers, and thus enables coordination by CAD file transfer in some instances.

Standardized Use of Levels: Naming of levels can aid in the use of CAD systems for coordination. Naming levels helps other engineers locate the parts of interest quickly. Further, standards for where design data is placed and where non-geometric information is placed can aid in the understanding of another engineer's work.

Network Transparency: The ability to easily access others' work and bring it into the current work area is important to using CAD systems for coordination. Incompatibility of systems and data files, or technical problems with communication networks can all affect the engineers' ability to work with others' CAD files.

Presence of a CAD Design Review Room: Another characteristic of the implementation of CAD technology that allows improvements in coordination is the presence of a CAD design review room- a room with a CAD terminal connected to a projection-screen television. Such rooms are helpful in using CAD to

coordinate work across groups (as discussed earlier).

9. Conclusions

There are four major conclusions from this study. First, there are some significant productivity benefits of CAD systems. Even if CAD systems are used solely as electronic drafting boards, some productivity gains will be achieved. Such gains, however, may not result in improvements in overall organizational effectiveness.

Second, CAD systems, when used as an aid to conversations, create a common language or set of references. This common language allows differentiated and interdependent groups to effectively communicate about design-related issues. The combination of a face-to-face meeting and the availability of a rich and flexible representation of the design lead to a medium of communication that is both unique and powerful.

Third, while CAD systems may be directly responsible for some changes in the way engineering work is done, many changes are only enabled by CAD systems. CAD systems do not necessarily decrease the time it takes to complete the design engineering phase, or to complete the product development process. CAD systems can lead to large improvements in productivity, but only if the work is reorganized to take advantage of the features of the systems. CAD systems' effectiveness as a communication medium allows them to be used as a gateway innovation- an innovation that is important for the other innovations it allows. CAD systems should be evaluated for their ability to enable productive design changes, and not expected to automatically cause changes.

Finally, the most productive changes enabled by CAD systems may entail what appear to be productivity losses at the group level. The use of CAD systems to improve coordination in the early stages of the design engineering process may result in more issues being raised early and more conflicts being resolved early. More work is done earlier, and the result is that it may take longer to complete some initial tasks. Schedules should be adjusted to allow these changes to occur, as the productivity gains downstream (e.g., in the prototype refinement phase) can be significant. It is important that these apparent productivity "losses" be recognized as an "investment," as they may lead to significant savings in the time it takes to complete the prototype refinement or process engineering phases.

Many companies are experimenting with or have implemented concurrent design methods. Concurrent design practices force the design engineer to work more closely with other groups when making design decisions. Rather than working with each other group sequentially and iteratively converging on a solution, a concurrent design process will require the design engineer to involve more groups in more design decisions. The communication demands are thus much greater.

Concurrent design has some clear benefits: a wider involvement in the design (1)

increases engineers' understanding of other groups' specialties and (2) changes engineers' relationships with other groups. Instead of only seeing a small part of the process, individuals from different groups are invited into the central flow of the product development process. This makes the conflicts that inevitably occur much less tense, and easier to resolve.

CAD systems have the potential to improve the ability to coordinate work within the product development process. If CAD systems are used to communicate design information, concurrent design meetings may become more productive, and the entire process may be more effective. Without the effective communication of design information enabled by CAD systems, concurrent design may be too inefficient to be worthwhile.

CAD systems will not cause any major changes by themselves, but may enable changes that can lead to significant productivity gains. Further, the simple use of CAD systems may not be sufficient to enable some changes- the way in which the systems are used is important. Managers must understand the capabilities and limitations of CAD systems, as well as the nature of the changes the systems enable, if they are to see a full return on their CAD systems investment.

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